

Discovery of giant ‘radio arcs’ in cluster Abell 3376: evidence for shock acceleration in a violent cluster merger?

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ABSTRACT

New multi-wavelength (radio, optical & X-rays) observational evidences are presented which show that the nearby ($z = 0.046$), rich cluster of galaxies Abell 3376 is experiencing a major event of binary subcluster merger. The key evidence is the discovery of a pair of large, optically unidentified diffuse radio sources (‘arcs’), symmetrically located about $2.6 h_{50}^{-1}$ Mpc apart at the opposite ends of the hot intra-cluster gas mapped by *ROSAT* in X-rays. It is argued that the gas-dynamical shock-waves, which occur naturally during cluster formation, are accelerating charged particles (cosmic rays) to relativistic energies, leading to synchrotron emission from the megaparsec scale radio arcs. If this is so, cluster Abell 3376 would also be a potential source capable of accelerating cosmic ray particles upto ultra-high energies (UHECR) of $E_{max} \sim 10^{18-19}$ eV. Thus this cluster is an excellent test-bed for understanding the physics of merger shocks and origin of enigmatic UHECR particles in structure formation process. Hence, Abell 3376 provides unique opportunities for further multi-wavelength observations with ground and space-borne observatories.

Key words: galaxies: clusters: general – galaxies: clusters: individual: Abell 3376 – X-rays: galaxies: clusters – radio continuum: galaxies – acceleration of particles – shock waves

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1 INTRODUCTION

The positive detection of many ultra high energy cosmic ray particles with surprisingly large energies in the range 10^{18} eV to a few times 10^{20} eV is one of the outstanding enigmas of Physics (Takeda et al. 1999; Hillas 1984). It can be shown that if such particles are accelerated by some as yet unknown mechanism, the energy requirements for the astrophysical sources are extraordinary (Hillas 1984). Beyond the ‘ankle’ of the cosmic ray spectrum ($\sim 3 \times 10^{18}$ eV), the Larmor radius of UHECR protons is too large to be retained by the $\sim \mu\text{G}$ field of our galaxy and therefore they are widely believed to be of extra-galactic origin. However, beyond the theoretical Greisen-Zatsepin-Kuz’mín (GZK) energy cutoff (~ 50 EeV), which is the proton energy threshold for the photo-pion production on collision with cosmic microwave background photons (CMB), significant energy losses result. In case of γ -ray primaries, pair creation through interaction with background photons (CMB, IR and radio waves) is most important in a wide energy range above the threshold of $\sim 4 \times 10^{14}$ eV (cf., review by Nagano & Watson 2000). Due to these ubiquitous energy losses, not only it is extremely difficult to accelerate particles to $\sim 10^{18-21}$ eV, but the high energy cosmic accelerators should probably be found within a horizon of ~ 100 Mpc of the observer. So far no astrophysical cosmic accelerator is visible in the directions from where UHECRs come, but AGN radio-lobes, AGN central regions, neutron stars, gamma-ray burst sources and galaxy clusters, all have been proposed as the potential sites for UHECR acceleration (Nagano & Watson 2000 and references therein). Therefore, identification of nearby accelerator sources capable of creating highest energy particles is obviously of great importance.

The largest and the most massive virialized structures are the galaxy clusters which assemble through the hierarchical process of gravitational infall of smaller mass components. In this process, the accretion of intergalactic matter and collision and merger of smaller groups and clusters take place mainly along the axes of large filaments of galaxies of length of a few Mpc to up to ~ 100 Mpc. During a merger, the enormous kinetic energy of colliding subclusters ($\sim 10^{63-64}$ erg) is dissipated in the form of shock-waves which play a pivotal role in heating of the intra-cluster medium (ICM) to the virial temperature. These Mpc size super-sonic ‘merger shock’ fronts (of Mach numbers $M \sim 2 - 5$) have recently been identified in high angular resolution *Chandra* X-ray observations, showing spatial variations of gas temperature and entropy within the intra-cluster medium (e.g., Forman et al. 2001). It is also expected that in the peripheral regions of evolving clusters, there should form

large-scale ‘accretion shocks’ due to supersonic convergent flows of background inter-galactic plasma (Quilis 1998; Miniati et al. 2000).

Due to their massive energies, large sizes and long lifetimes, the shocks, in and around the clusters, are potential sites for the acceleration of very high energy cosmic-rays (CR) up to $10^{18} - 10^{19}$ eV, near the ‘ankle’ region of CR spectrum (Norman 1995; Kang, Ryu & Jones 1996), and they may also be the seeds for the ICM magnetic fields (Kulsrud et al. 1994). Recently it has been pointed out that the cosmic-ray ions accelerated at intergalactic shocks could accumulate in the formed structure, storing a significant fraction of the total energy there (Miniati et al. 2001(b)). The connection between non-thermal radiation and cluster mergers has been recently highlighted (Blasi 2001; Sarazin 2002). Direct evidence for the ability of cosmic shock waves to accelerate particles is given by the observed association of the so called cluster ‘radio relic’ sources with locations where shock waves are expected from X-ray observations (Enßlin et al. 1998). Diffusive shock acceleration may be operative at these locations and responsible for the radio emitting electrons. In this context, perhaps the strongest evidences are provided by the discovery of large, diffuse ‘radio-arcs’ in merging cluster Abell 3667 by Rottgering et al. (1997), and by the first evidence of shock accelerated relativistic particles and magnetic fields in a super-cluster scale collapsing filament of galaxies ZwCl 2341.1+0000 by Bagchi et al. (2002). Recently, it has been pointed out that some ‘radio relics’ in clusters could be the shock wave rejuvenated fossil remnants of former active radio galaxies (Enßlin & Gopal-Krishna 1998). Although the role of shocks in accelerating cosmic-ray particles up to $\sim 10^{15}$ eV ‘knee’ energies in supernova blast waves is beginning to be understood (e.g., Enomoto et al. 2002), much remains mysterious about the astrophysical aspects of particle acceleration in large-scale structure formation (Bagchi et al. 2002).

This paper describes the optical, X-ray and radio evidence for an energetic merger in A3376 and, reports the discovery of a pair of giant radio arcs (Sect. 2). In Sect. 3, I discuss the possibility of shock acceleration origin of the radio emission and the implied acceleration of higher energy cosmic ray particles. The main conclusions and the outlook for future research are summarised in Sec. 4. For a cluster redshift of 0.046, 1 arcmin corresponds to $74.16 h_{50}^{-1}$ kpc, with the Hubble constant expressed in units of $50 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2 EVIDENCE FOR MERGER IN OPTICAL, X-RAY & RADIO WAVELENGTHS

The cluster Abell 3376 (A3376 or DC 0559-40) is an X-ray bright cluster, which was selected for study due to its remarkable X-ray morphology. It is a member of the sample of *ROSAT* X-ray-brightest Abell-type clusters [XBACs; Ebeling et al. 1996. The 0.1-2.4 keV band luminosity is $L_X = 2.48 \times 10^{44} \text{ erg s}^{-1}$], and also of the *Einstein Observatory* cluster sample (Jones & Forman 1999). This southern cluster (R.A. $06^h00^m43^s$ (J2000), Dec. $-40^\circ03'00''$, Bautz-Morgan class I), at the redshift $z=0.046$ (Dressler & Shectman 1988(a)), is located only $267 h_{50}^{-1}$ Mpc away and shows several evidences of ongoing energetic merger activity. The optical galaxies are distributed in a bar-like structure (projected), extending along a position angle of $\approx 70^\circ$, defining the merger axis. The two brightest cluster members are located near the centers of major subcluster of galaxies which are lined-up along the same position angle (Dressler & Shectman 1988(b); Escalera et al. 1994). Fig. 1 shows the optical photograph where the location of two brightest cluster members (shown encircled), and other catalogued galaxies ('+' marks; Dressler & Shectman 1988(a)), have been plotted. A strong radio source MRC 0600-399, showing sharply bent radio jets, is found associated with the bright 'E' galaxy positioned at the *ROSAT* X-ray peak (Fig. 1 & 5). This source also provides important evidence for a merger. The relationship between its radio structure and the hydrodynamics generated by merger is further discussed below.

The *ASCA* observations by Markevitch et al. (1998) report a low emission weighted gas temperature ($kT = 4.0 \pm 0.4$ keV) and absence of any cooling flow, consistent with the previous findings that cluster mergers probably disrupt cooling-flows (e.g., Edge, Steward & Fabian 1992). The X-ray data from *ROSAT* archives further confirms the merger scenario. It reveals a highly disturbed, non-equilibrium state of the intra-cluster gas, and the bremsstrahlung X-ray emission elongated along the same direction as the optical axis of the colliding groups (i.e., p.a. $\approx 70^\circ$, hereafter called the 'merger-axis'). In addition, there are clear evidences for striking surface-brightness asymmetry: i.e., an off-centered 'cometary' shape, centroid shift, and pronounced twisting and compression of the inner isophotes near the X-ray peak (see Fig. 2). All these features are possibly indicative of an off-axis merger scenario (Ricker 1998; Takizawa 2000).

The cross-correlation of *ROSAT* X-ray data with VLA 1.4 GHz NVSS atlas (Condon et al. 1998) reveals perhaps the most interesting aspect of this cluster: a pair of very large and

diffuse radio sources (the ‘radio arcs’ hereafter), located at the opposite ends of the extended X-ray emitting gas, about $36'$ or $2.6 h_{50}^{-1}$ Mpc apart from each other. These features are shown as radio countours (Fig. 1) and as gray-scale image (Fig. 2), overlaid on the optical and X-ray images of A3376. Fig. 3 & 4 show detailed images, where the radio contours are superposed on the UK Schmidt Telescope optical images. There is no convincing evidence for any optical galaxy obviously associated with the radio arcs, and hence they are unlikely to be the canonical cluster radio galaxies. It is also implausible that they are radio-lobes of a single giant radio galaxy (GRG), as no obvious radio link (jets or plumes) between them and any central optical galaxy is visible, and GRGs of this large size ($> 2h_{50}^{-1}$ Mpc) are extremely rare (Schoenmakers et al. 2001). On the other hand, the symmetric and tangential juxtaposition of the radio arcs relative to the merger axis, the brightest cluster galaxies, and relative to the X-ray contours (see Fig. 2) argue strongly that they are part of this cluster and very likely originate in a large-scale energetic process linked to the merger activity.

3 DISCUSSION & OUTLOOK FOR FUTURE

Since the diffuse radio emission is probably the synchrotron radiation, one may ask - what could be the source of relativistic electrons and magnetic fields powering the radio arcs observed so far ($\approx 1.3 h_{50}^{-1}$ Mpc) from the cluster center? In this respect, the problem is similar to that of the origin of radio halos, which require a cluster scale accelerator source in order to energize electrons distributed over Mpc scales (Jaffe 1977). The radiative life time t_{IC} of an electron with Lorentz factor γ in a weak ($B < 3 \mu\text{G}$) magnetic field is dominated by inverse Compton scattering (IC) on CMB, which is, $t_{IC} \approx 2.3 \times 10^8 \left(\frac{\gamma}{10^4}\right)^{-1} (1+z)^{-4}$ yr. The frequency of associated synchrotron emission is $\nu_{\text{syn}} \approx 4.19 \times 10^8 \left(\frac{\gamma}{10^4}\right)^2 \left(\frac{B}{\mu\text{G}}\right)$ Hz, and $\gamma \approx 18300$ (energy $E_e = 9.35$ GeV) for $\nu_{\text{syn}} = 1.4$ GHz, the frequency of radio detection.

The 3D structure of ICM magnetic fields in merging clusters is yet unknown. Nevertheless, according to simulations, it is likely to be both significantly tangled on various spatial scales and turbulent (Dolag et al. 1999; Roettiger, Stone & Burns 1999), which will severely restrict the diffusion of charges from their point of injection. In the limit of Bohm type diffusion (diffusion coefficient $D_B(p) \propto p$, the particle momentum), corresponding to scattering on saturated field fluctuations, the diffusion length within the IC cooling time is $l_{diff} \approx (D_B t_{IC})^{1/2} = 11.36 \left(\frac{B}{\mu\text{G}}\right)^{-1/2}$ pc. Therefore, initial acceleration at a central source such as an AGN and diffusive transport upto \sim Mpc scale is not possible. The discrepancy

between the Bohm diffusion length-scale and the radio structure size is so large that, even with inclusion of advective transport by bulk flows and more effective diffusion in ordered magnetic fields, electrons are still unable to cross the emission region within a radiative life-time. It is clear that some form of *in situ* acceleration mechanism is called for.

Further detailed multi-wavelength observations and computational study of the phenomenon are underway in order to understand the details of acceleration process involved. Here, it is argued that most plausible explanation is the diffusive shock acceleration (DSA) (Bell 1978; Blandford & Ostriker 1978) of cosmic ray particles (electrons, protons and ions) on the shock fronts, putatively located near the radio arcs. The prevailing physical conditions of the disturbed ICM: large-scale bulk flows, turbulence, and collisionless MHD shocks, all provide ideal environment for particle acceleration through stochastic Fermi mechanism (Drury 1983), and amplification of seed magnetic fields.

Some important clues to the dynamical history and the energetics of acceleration process can be obtained from the morphology, flux density, and position of the radio arc pair relative to the cluster center. The radio peaks of the western and eastern arcs are located at the positions (J2000) R.A. $06^h00^m3^s.09$, Dec. $-40^\circ04'25.0''$ (5 mJy/beam, 10σ detection) and R.A. $06^h02^m59^s.66$, Dec. $-39^\circ54'56.1''$ (4 mJy/beam, 8σ detection), and their 1.4 GHz integrated flux densities are 82 ± 5 mJy and 32 ± 3 mJy respectively. It is noticeable that both of them are curved, with concave side facing the cluster center, and precisely positioned such that a line joining their radio peaks would run parallel to the merger axis at the position angle $\approx 70^\circ$. The center of symmetry falls near the center of cluster located on the merger axis at the approximate sky position R.A. $06^h01^m30^s.0$, Dec. $-39^\circ59'50.0''$ (shown by a large cross in Fig. 2). The projected morphology of radio arcs approximately being the arc sectors from a circle of radius $\approx 18' \equiv 1.3 h_{50}^{-1}$ Mpc, centered at this position (see Fig. 2). In addition, they also display a distinctive inversion symmetry – in the sense that if in the western arc radio emission extends to the north of merger axis, the emission extends to the south of this axis in case of the eastern arc, thereby forming a ‘S’ shaped pattern (Fig. 2).

These observations suggest a causal relationship between the radio structures and the outward propagating shock waves that probably originated near the cluster center $\gtrsim 1.3 \times 10^9$ yr in the past (assuming constant shock speed of ~ 1000 km s $^{-1}$). These shock waves are likely to be gravitationally induced due to observed merger event of subclusters. The integrated radio luminosity of west(east) arc is $L_{\text{sync}} = 9.84(3.84) \times 10^{40} h_{50}^{-2}$ erg s $^{-1}$ (over 10 MHz-100 GHz frequency range and assumed sp. index $\alpha = -1$). Considering additional IC

energy loss, and a magnetic field $B < 3 \mu\text{G}$, the total radiative losses add up to $L_{\text{sync+IC}} \approx 1.4 \times 10^{42} \text{ h}_{50}^{-2} \text{ erg s}^{-1}$. Any accelerating process must be energetic enough in order to generate at least this much amount of non-thermal radiation from electrons.

One can obtain some order of magnitude estimates by considering the scenario of particle acceleration in binary cluster merger shocks (e.g., Sarazin 2002). Numerical simulations of cluster merger events (Ricker 1998; Takizawa 2000; Miniati et al. 2001(a)) demonstrate that these can be very energetic, liberating gravitational energy of order $E_{\text{grav}} \approx 2.24 \times 10^{63} (\frac{M}{2 \times 10^{14} M_{\odot}})^2 (\frac{d}{1.5 \text{ Mpc}})^{-1} \text{ ergs}$, for two cluster masses M , at the collision distance d . The gas dynamics is very complex and the fluid velocities involved are generally super-sonic – typically $v_{\text{shock}} \sim 2000 \text{ km s}^{-1}$ (v_{shock} is shock velocity). The merger lasts for a duration $t_{\text{merger}} \approx d/v_{\text{shock}} \sim 10^9 \text{ yr}$ (which is also the duration of acceleration). Consequently, the rate of gravitational energy dissipation is given by $L_{\text{grav}} \approx E_{\text{grav}}/t_{\text{merger}} \sim 7.1 \times 10^{46} \text{ erg s}^{-1}$. Thus, typically L_{grav} is much larger than $L_{\text{synch+IC}}$ and only a modest fraction of total energy is needed to accelerate the cosmic ray particles. The main channel of dissipation of this energy would be the shock heating of ICM upto $T_{\text{gas}} \sim 10^{7-8} \text{ K}$. Radio observations of supernova shocks with similar $v \gtrsim 10^3 \text{ km s}^{-1}$ speeds show that they are capable of converting at least a few percent of shock energy into the energy of relativistic electrons (e.g., Blandford & Eichler 1987).

The presence of diffuse radio emissions ahead of merging subclusters, marked by bright optical galaxies, suggests that they may be located at the shock fronts where in situ DSA is a strong possibility. This morphology of arcs is reminiscent of a classical detached bow shock that preceeds a blunt-body in supersonic flight within a fluid. The elongation of X-ray contours and the subcluster of galaxies in the same direction (Fig. 2) suggests that the clusters associated with the bright X-ray core and the cD galaxy are flying away from each other, possibly $\sim 1 \text{ Gy}$ after their closest encounter. However, the ‘S’ shaped inversion symmetry and curvature of the radio arcs indicate that the leading bow shocks have possibly assumed a spiral shape due to an off-centered collision event (i.e., one with a finite impact parameter, instead of being head-on), leading to orbital motion of coalescing masses about their common center of mass. It is even possible to infer this sense of rotation from the radio maps shown, which suggest a clock-wise motion. The pronounced clock-wise rotation of isophotes near the *ROSAT* X-ray peak, directed towards a compressed region on top (Fig. 2), also suggests this point (see Ricker 1998 and Takizawa 2000 for numerical simulations of this geometry).

From very general principles based on DSA framework, one can derive the critical parameters of particle acceleration in a merging system such as A3376. The mean acceleration time-scale $t_{acc}(E)$ for a particle to reach energy E is determined only by velocity jump at the shock and the diffusion coefficients (Drury 1983), i.e., $t_{acc}(E) = \frac{3}{(u_1 - u_2)}[(D_1/u_1) + (D_2/u_2)] \approx (8/u_1^2) D_B$. Here $u_1(u_2)$ is the up(down) stream flow velocity and $D_{1,2}$ are the respective diffusion coefficients. The approximation assumes a strong shock of compression ratio $r = (u_1/u_2) = 4$, a frozen-in field condition $(B/\rho) = const.$, $(D/u) = const.$ across the shock, and Bohm diffusion limit. Under these conditions $t_{acc} = 8.45 \times 10^5 u_3^{-2} E_{15} B_\mu^{-1} Z^{-1}$ yr, where $E_{15} = (E/10^{15} \text{ eV})$, $u_3 = (u_1/10^3 \text{ km s}^{-1})$, $B_\mu = (B/10^{-6} \text{ G})$, and Ze is the nuclear charge. The DSA naturally results in a power-law for particle energy or momentum function $f(p)$ such that $f(p) \propto p^{-b}$, where p is momentum and b is the power-law slope. The synchrotron spectrum should also be a power-law of the form $I(\nu) \propto \nu^{-\alpha}$, where spectral index $\alpha = (b - 3)/2$. The index b is related to the compression ratio r such that $b = 3r/(r - 1)$, and $r = 4$, $\alpha = 0.5$ for a strong shock in a gas of specific heat ratio $\Gamma = 5/3$. Downstream of the ‘acceleration zone’, a ‘diffusion zone’ showing gradually steepening spectrum is to be expected, which forms due to electrons undergoing diffusion and advection with the fluid flow and suffering IC and synchrotron energy losses. Detailed VLA and GMRT radio spectral and imaging observations of this cluster are underway in order to test these predictions from the DSA theory. The *Chandra* and *XMM-Newton* X-ray telescopes would possibly be able to detect the temperature and density jumps associated with the shock fronts. These future observations would provide a more definite proof of the particle acceleration scenario proposed for this cluster.

For protons, which suffer negligible radiative losses (below 50 EeV), the highest acceleration energy (E_{max}^P) is probably limited by the finite life time of shocks, i.e., $t_{acc} = t_{merger} \sim 10^9 - 10^{10}$ yr, thus giving $E_{max}^P \sim 10^{18-19}$ eV. The heavier nuclei with $Z > 1$ would be accelerated to even higher energies compared to protons. For cosmic ray electrons the situation is different due to their significant radiative losses in synchrotron and IC radiation. The maximum energy attained by electrons (E_{max}^e) is governed by condition that $t_{acc} \lesssim t_{rad} < t_{merger}$, and if IC loss dominates over the synchrotron ($B < 3 \mu\text{G}$), one obtains $E_{max}^e \sim 3.73 \times 10^{13} u_3 B_\mu^{1/2}$ eV. More detailed hydrodynamic simulations by Kang, Ryu & Jones (1996) show that during gravitational in-fall and mergers at the sites of evolving clusters, energetic protons can be accelerated upto the GZK cut-off energy ~ 50 EeV, provided a magnetic field of $\sim 1 \mu\text{G}$

is available to diffusively trap the charge particles near the shock region, and if about 10^{-4} fraction of infalling kinetic energy can be converted as high energy particles.

It is likely that A3376 is a potential source which fits these conditions. The magnetic field strength in A3376 cluster is not known yet, but could be $\sim 1 \mu G$ (Bagchi, Pislár & Lima Neto 1998; Clarke, Kronberg, & Böhringer 2001). The diffuse synchrotron emission of radio arcs are ‘sign-posts’ for the existence of relativistic electrons and magnetic fields at $\sim \text{Mpc}$ distances from cluster center. Since diffusive Fermi-I process accelerates all type of charges (electrons, protons and ions), it is argued above that these structures can in fact be the efficient particle accelerators of very energetic cosmic rays. A3376 is near enough that some of these cosmic rays could actually be detected by the existing or future cosmic ray observatories, particularly the energetic inverse Compton X-ray and γ -ray photons upto extreme energies $h\nu \sim 100 \gamma_7^{e2} \text{ GeV}$ (where γ_7^e is the maximum electron Lorentz factor in units of 10^7). Observation of such particles would constitute a strong proof of the cluster shock origin of UHECR particles – evidence not available at the moment. On the other hand, compared to number of merger events, such cluster collision mediated dual shock-fronts appear to be quite rare, because as of today the only other known example of this phenomenon is a similar radio, optical and X-ray morphology observed in southern Abell cluster A3667 (Rottgering et al. 1997).

The NVSS radio survey has detected the catalogued strong radio source MRC 0600-399 (Large et al. 1981), associated with the bright ($m_{pg} \approx 14$) E-galaxy ($z = 0.04552$) positioned at the *ROSAT* X-ray peak (Figs. 1 & 2). The higher resolution VLA 4.8 GHz radio map shows that both the radio jets are bent backwards from the radio core in a wide ‘C’ shape (Fig. 5), characterizing it as a wide-angle tail (WAT) source. WATs are only found in galaxy clusters and are excellent probes of the gas-dynamical processes occurring during a merger (Gomez et al. 1997). Interestingly, here the northern and southern radio jets both appear to be swept back along position angles of $72 \pm 5^\circ$ and $60 \pm 5^\circ$. Therefore, even though affected by projection effects, they appear to be roughly following the merger axis delineated by optical, radio and X-ray data (Fig. 5). This not only indicates correlated structural distortion, but could also be a good proof of the plausible hypothesis (e.g., Roettiger et al. 1996) that ram-pressure from bulk gas flows of speed $\sim 10^3 \text{ km s}^{-1}$, resulting from mergers, are responsible for bending of radio-jets in WAT objects in clusters, and not the actual motion of the parent galaxy with such high speed. Thus one can actually use this radio source as a ‘wind-sock’ to

infer which way the cluster wind blows. Hence, more detailed radio and X-ray observations and modelling of this radio source are likely to prove very instructive.

4 CONCLUSIONS

In this paper, I have presented several new observational evidences which show that the nearby cluster of galaxies A3376 is undergoing a major merger event of subclusters. The most striking is the discovery of a pair of optically unidentified, diffuse, giant radio arcs, located $2.6 h_{50}^{-1}$ Mpc apart, symmetrically straddling the hot intra-cluster gas imaged by *ROSAT*. It is argued that the likely origin of this Mpc scale radio emission is *in situ* acceleration of relativistic charged particles in gas-dynamical shock-waves, which occur naturally during cluster formation. Probably the energetics of shocks in A3376 are strong enough to accelerate cosmic ray particles upto ultra-high energies of $E_{max} \sim 10^{18-19}$ eV. Thus this cluster is an ideal test-bed for elucidating the origin of enigmatic UHECR particles in structure formation shocks. Hence, Abell 3376 is also a target of choice for more detailed multi-wavelength observations in near future.

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Figure 1. The VLA 1.4 GHz (NVSS survey) radio contours are shown overlayed on the UK Schmidt Telescope optical image. The radio beam size ($45''$ Gaussian) is shown by a circle (box at lower left corner) and the contour levels in multiples of 1 mJy/beam are listed at the bottom. The r.m.s. value of the background noise is ≈ 0.5 mJy/beam. Circles locate the two brightest cluster members and the ‘+’ marks are galaxies from the Dressler catalogue (Dressler & Shectman 1988(a)). The brightest cD galaxy is inside the circle at lower right. Note the region of missing radio data towards the south.

Figure 2. *ROSAT* PSPC broad band (0.1-2.4 keV) X-ray image in contours, overlayed on the VLA 1.4 GHz NVSS survey radio data shown in gray scale (Note the missing radio data towards the south). Smaller circles locate the two brightest cluster galaxies and their subclusters (as in Fig. 1). To emphasize the inherent symmetries, a large circle passing through the radio arcs is drawn at the cluster center (at the large ‘+’ mark), and the merger/symmetry axis is drawn using a dashed line (see text for details).

Figure 3. VLA NVSS survey 1.4 GHz radio map showing the eastern radio arc. In the background, the UK Schmidt Telescope optical image can be seen. The radio beam size ($45''$ Gaussian) is shown by a circle and the contour levels, in multiples of 1 mJy/beam, are listed at the bottom. The r.m.s. value of the background noise is ≈ 0.5 mJy/beam.

Figure 4. VLA NVSS survey 1.4 GHz radio map showing the western radio arc. In the background, the UK Schmidt Telescope optical image can be seen. The radio beam size ($45''$ Gaussian) is shown by a circle and the contour levels, in multiples of 1 mJy/beam, are listed at the bottom. The r.m.s. value of the background noise is ≈ 0.5 mJy/beam.

Figure 5. The VLA 4.8 GHz (archival data) radio map of the central bent- jet radio source MRC 0600-399, located at the *ROSAT* X-ray peak and associated with a bright E-galaxy. The UKST optical image is shown in the background. The contour are drawn at -0.2,-0.1,0.1,0.2,0.4,0.8,1.6,3.2,6.4,12.8 & 22 mJy/beam. The $24''$ Gaussian beam is drawn at the lower left corner.